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Sammendrag:

Relasjoner mellom klimaparametere og fiskeriparametere har blitt undersøkt ved hjelp av FJOMP-databasen (fiskeri, jordobservasjon, modellering og prediksjon).

FJOMP-databasen inneholder fysiske- og fiskeriparametere relatert i de nordiske hav og Barentshavet. Vesentlige deler av databasen er basert på havmiljøparametere avledet fra in-situ-målinger og satellitt-jordobservasjoner. Korrelasjoner mellom fisk og klima er systematisk undersøkt, og flere interessante koblinger er funnet. De mest interessante er presentert i denne rapporten.

Summary:

See Abstract page 2

Emneord:	Subject heading:
1. Klima	**1.** Climate
2. Fisk	**2.** Fish
3. Jordobservasjon	**3.** Earth observation

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Prosjektleder

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Seksjonsleder

Fisken og havet 12-2002

Climate-fish relations in Norwegian waters

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Abstract

Climate variability and change in the Arctic and Sub-Arctic regions have become increasingly important issues over the past few decades. The goal of the Arctic Climate Impact Assessment (ACIA) is to evaluate and synthesize knowledge on climate variability, climate change, and increased ultraviolet radiation and their consequences. Combined analysis of marine data records based on field observations and satellite Earth observation data records are being investigated in order to determine the relations between the variability in the marine physical and biological environment. The increased availability of satellite Earth observation data during the last 30 years have improved the role of use of these type of observations in the assessment of longer term variation in marine ecosystems. This report is mainly based on results from the FJOMP project (Fishery, Earth observation, Modeling and Prediction). The goal of the FJOMP project is to elaborate the use of satellite based information about the marine environment in the studies of the variability in the fish recruitment and stock assessment.

The response of climate variation on the fish population is not well understood. In many stocks knowledge of the relationship between larvae and recruits and between recruits and spawning stock biomass is poor. Identifying which climate variables that have an impact on the fish at its different life stages may improve the knowledge of these relationships.

Under the project FJOMP, a database, with the same name, with fishery and climate (mostly satellite based) time series was established. At this stage more than 40 climate and more than 30 fishery time series are included in the database. This database serves as a platform for a statistically approach in search for climate variables of importance for the fish populations.

The effect of climate variation on fish recruitment and stock status has been investigated. In this study we have focused mainly on the relations between the ocean physical climatology and the three species, North East Arctic cod, Norwegian spring spawning herring and Barents Sea capelin. Climate and fishery time series in the FJOMP database have been systematically correlated, also with time lag, in order to search for interesting relationships. Also, multiple regression models have been used to further improve some of the most interesting correlations found.

It is not the intent of this report to give deeper discussions on mechanisms and processes that link the climate variability to the fish populations, but instead give a taste of what this kind of linkage can give of contribution to the understanding of climatically effects on fishery recruitment and fish population variation.

The results show that the North Atlantic Oscillation index (NAO) index and the sea surface temperature (SST) in general are two important climate variables for fish recruitment (however, they are not independent as NAO have a large impact on SST). Especially the NAO index gives good relations to several recruitment parameters for North East Arctic cod, while SST is more important for Barents Sea capelin and Norwegian spring spawning herring. In addition sensible heat flux, ice cover and heat transport are other important climate variables, which are related to the variability of the various fish classes and recruitment.

Contents

1. Introduction

Climate variability and change in the Arctic and Sub-Arctic regions have become increasingly important issues over the past few decades. These issues have also prevailed in the international scientific and political scene for over a decade through major programs of scientific research, through intergovernmental assessments and through international treaties, protocols and conventions. The results of scientific research and indigenous knowledge have increasingly documented climate related changes that are more evident in the Arctic region than in other regions of the world or are critical to our understanding of global-scale climatic processes. The effect of climate variability on the ecosystems around the Arctic is of major concern, and Arctic Climate Impact Assessment (ACIA) will touch on all issues related to climate impacts in their report that will be published in 2004 (see http://www.acia.uaf.edu for further information).

The goal of the ACIA is to evaluate and synthesize knowledge on climate variability, climate change, and increased ultraviolet radiation and their consequences. The aim is to provide useful and reliable information to the governments, organizations and peoples of the Arctic on policy options to meet such changes. Climate variability and change, and more recently, notable increases in UV radiation, have become important issues in the Arctic over the past few decades. The ACIA will examine possible future impacts on the environment and its living resources, on human health, and on buildings, roads and other infrastructure. Such an assessment is expected to lead to the development of fundamental and useful information for the nations of the Arctic region, their economy, resources, and peoples. This report is a small contribution the ACIA program, and addresses effects of climate on fish recruitment.

The response of climate variation on the fish population is not well understood. For many stocks the relationship between larvae and recruits and between recruits and spawning stock biomass is poor, basically because of the strong climate impact on the survival at early life stages masks the relations to older fish. Identifying which climate variables that have an impact on the fish at its different life stages may improve these relationships.

In order to search for relations between fishery time series and climate variables a database, FJOMP (Fishery, Earth Observation, Modelling and Prediction) was established by Nansen Environmental and Remote Sensing Center (NERSC) and the Institute of Marine Research (IMR) under contract with the Norwegian Space Centre (NSC). The FJOMP database serves as a platform for a statistically approach in search for climate variables important for fish populations. Through systematic correlation of the different climate and fishery time series in the database and development of multiple linear regression models some of the significant climate variables have been identified.

The goal of this report is to give examples of the possibilities, and a taste of the potential, with the kind of linkage between climate and fishery data that is possible with the FJOMP database. It is not the intent of this report to give deeper discussions on mechanisms and processes that lay behind the relationships. In the following the most profound and interesting results are presented. The regression models are novice, and are still under evaluation in search for better fit (Pettersson *et al.*, in press). However, the fit of the model are encouraging, and the models might at present prove useful, e.g. as background information in fish stock assessment.

In some cases there is a time lag between the controlled variables and the response variable in the regression models, accordingly it is possible to make a prognoses that can be helpful in fishery assessment and management.

2. *Methods*

2.1 Short description of the database and the major datasets

The FJOMP database:

The database consists at present of more than 40 climate parameters and more than 30 fishery statistical time series. The climate data are gathered from global databases (the most important will be described below), extract time series from the 3D ocean circulation models NORWECOM (Skogen and Søiland, 1998) and MICOM (Brusdal, *et al.*, 2002) (e.g. salt- and heat- transport and velocity through selected sections), ice models, field data and environmental indices. The data are in NetCDF format, and tool for accessing the data and run correlations is developed in MATLAB scripts.

The NCEP database:

The data (http://www.cdc.noaa.gov/cdc/reanalysis/) from the NCEP/NCAR (National Centers for Environmental Predictions / National Center for Atmospheric Research) reanalysis project is from a model, which uses data assimilation using past data from 1948 to the present. A subset of this data has been processed to create monthly means of a subset of the original data. The data assimilated into the model is from e.g. ships, buoys and satellites. In FJOMP several of the available NCEP datasets are gathered, e.g. skin temperature, sensible heat flux and ice coverage. The resolution of the grid cells are 1.9047 degree latitude and 1.8750 degree longitude.

The MONARC dataset:

The database contains ice-coverage data. The sea ice concentration are derived from SSM/I and SMMR satellite data by the use off the NORSEX algorithm (Svendsen *et al.*, 1983).

The IGOSS dataset:

The IGOSS (Integrated Global Ocean Services System) dataset is provided by the International Research Institute for climate prediction (IRI) from their website (http://ingrid.ldeo.columbia.edu). The dataset contains Sea Surface Temperature (SST), which is based on data from ships, buoys and satellites. The resolution of the grid cells is 1 degree in both latitude and longitude.

The NAO index:

The North Atlantic Oscillation index (NAO) is an index based on the pressure gradient between the Iceland low-pressure area and the south European high-pressure area (Lisboa and Gibraltar). This index is often used as a proxy index for the weather system influencing the wind field along the Norwegian coast, and thereby also the transport of warm Atlantic water into the Norwegian Sea. The data is uptained from the website (http://www.met.rdg.ac.uk/cag/NAO/index.html)

Fishery datasets:

The fishery datasets are a collection of survey data and assessment model data gathered from IMR and ICES (International Council for Exploration of the Sea). The data from ICES is mainly from assessment models (VPA, Virtual Population Analysis), and found in the report from the different workgroups. These reports can be found at http://www.ices.dk/.

2.2 Statistical correlation methods

Correlations between the environmental and fisheries time series have been calculated using the various variables included in the FJOMP database. In the case of surface data, e.g. NCEP (Kalnay *et al.* 1996) and IGOSS (Reynolds,1988; Reynolds and Smith, 1994), the correlations are calculated between the fisheries time series and the time series at each grid point of surface field of the environmental data set.

In the correlation analysis time lag of 0 to -3 years (environmental data 0 to 3 year before the fishery data) have been evaluated in order to identify the best statistical match up. This statistical analysis has been set up to automatically evaluate the wide range of possible relations between the parameters in the FJOMp database.

In the case where the correlations are better than +/- 0.75 the result have been shown graphically and correlations higher than +/- 0.70 have been listed in a table for further individual inspections and analysis. For surface covering environmental data, a correlation map is plotted along with the time series of the grid point with the highest correlation with the fisheries series. Two additional plots are also made:

1) Fishery time series and NAO index (with zero timelag),
2) Fishery time series and NCEP sea ice index in ICES fishery area IIb (see Fig. 1).

In the case of monthly environmental data the correlations have been runed for each individual month, except June and November due to computer limitations.

In the case of a surface related field the correlations are only interesting if they occur in the same geographical area as the fish data, or in an area that are within a reasonable advective distance for the given time lags used. This is the main strength of the correlation map, where interesting regions of higher correlations are easily spotted. At the same time these correlations maps can serve as a tool for researchers in their planning of field investigations as they show where not to search.

2.3 Multiple regressions

Multiple regression models/analysis, with starting point in the methods of Svendsen *et al.* (1995), have been developed and tested on recruitment variables of North East Arctic cod, Norwegian spring spawning herring and Barents Sea capelin. Several parameters and time lags periods (0-5 year) have been evaluated. The variables have been selected on the basis of current knowledge and results from the correlation runs. A major issue during this process was to be able to make prognoses, which means that we were especially looking for variables with time lag that further might be used in the prediction of following years. However, we want to emphasis that though this is "a needle in a haystack" method it has given promising results. The potential of the FJOMP database is large in this respect, and we have so far only "scratched" the surface on this matter.

2.4 Pressure fields and changes in cod at age distribution

The time development of the age distribution of North East Arctic cod have been examined by dividing the spawning stock biomass into three age groups, 3-7 year olds, 8 year olds and 9 year and older.

The change in climatic average position of the sea surface pressure field center over Iceland has been investigated by dividing the time series into two main periods, 1948-1975 and 1975-1999. Only the winter months have been used in the analysis. The mean and standard deviation for each period has been calculated, as well as the difference in mean and standard deviation between the two time periods.

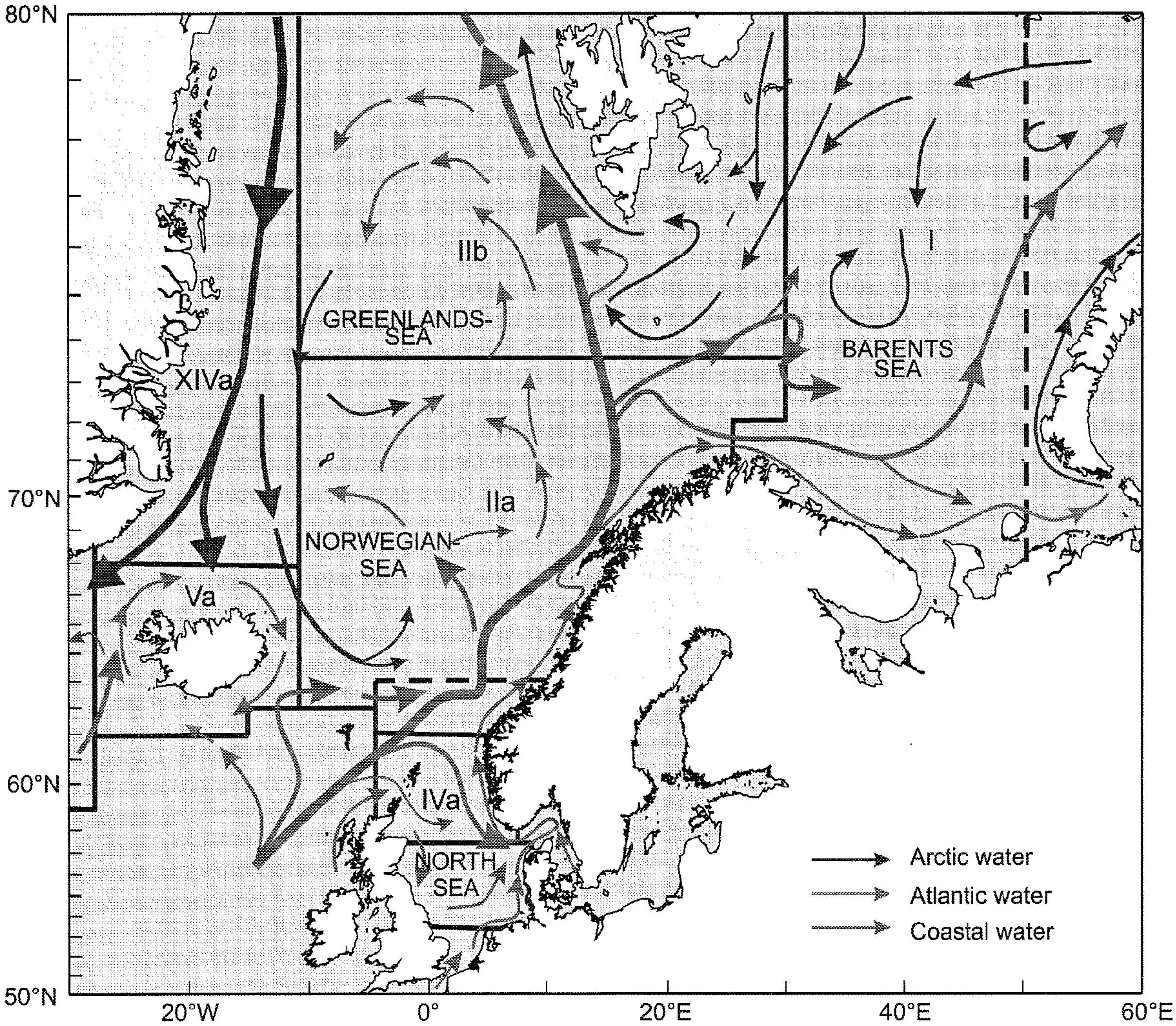


Figure 1. Overview of the major current systems in the Nordic Seas and the Barents Sea, together with the ICES fishery statistics areas in the same region.

3. Results and discussion

Though a high number of good correlations that have been found, there are many of the couplings that are unlikely, or at present the connection is not known or are very speculative. However there are several connections that are very interesting. Both because they give the possibility of foresee the future, due to time lag between them, and because they may have a simple and explainable connection chain. Only the most promising results, both in the sense of explainability and high value are presented here.

Further, emphasis has been put on the analysis of fishery parameters related to stock recruitment, where climate are believed to make the largest direct impact. In the following the word "recruitment" will be used in its most wide sense, from the larvae stage up to the age at which the young fish becomes viable for commercial fishery. For cod and herring this occur at the age of three year and for capelin at the age of one year.

3.1 The North Atlantic Oscillation (NAO) and recruitment

A strong correlation (r=0.82) was found between the 0-group log index for North East Arctic cod in the Barents Sea and NAO winter index two and a half years before (Fig. 2). This may have to do with food supply for the cod larvae. We know that there is a connection between zooplankton biomass and NAO index the previous year (Melle and Holst, 2001) which may be related to overwintering of zooplankton in the Norwegian Sea, and the following recruitment (high numbers of overwintering adults gives good recruitment the following spring, and visa versa). The second year might be explained by the advective transport of zooplankton towards the Barents Sea, where the 0-group of cod is located. The combined effects of these relations may accordingly explain the response lag of two years between the NAO and 0-group index.

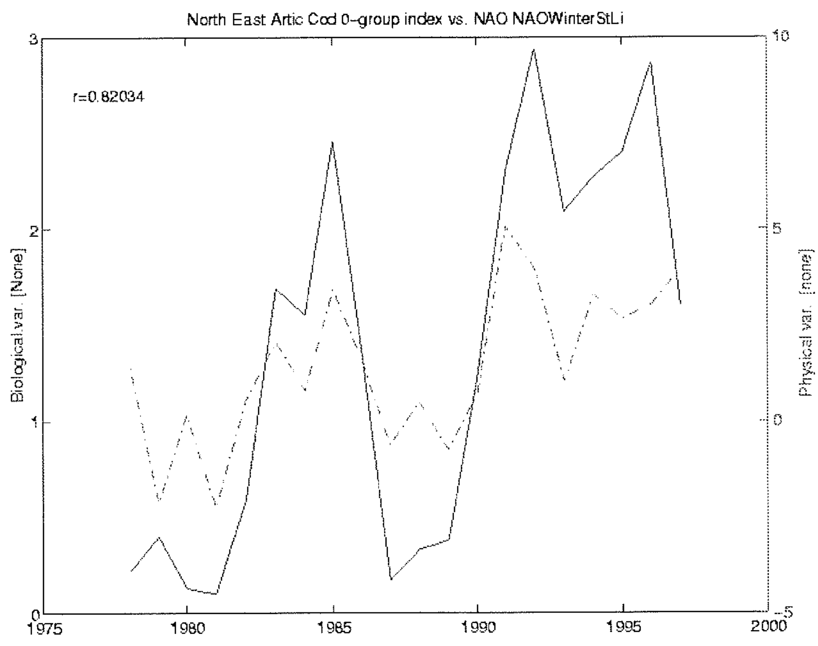


Figure 2. Relationship between 0-group index (log) of North East Arctic cod(solid line) and NAO winter index (Lisboa-Island) 2.5 year before(dashed line). The correlation coefficient is 0.82. Note that the timescale is for the biological (Ogroup) variable.

3.2 Sea surface temperature (SST) and recruitment

The IGOSS sea surface temperature distribution in January is correlated with the 0-group log index of North East Arctic cod the same year (Fig 3). The highest positive correlations are found in two areas, the southeastern part of the Barents Sea and in the Nordic Seas, with maximum correlation of r=0.87 (central Nordic Seas).

It is especially interesting with the high correlation obtained in the South Eastern part of the Barents Sea, which is part of the juvenile breeding area for the cod. The larger correlation in the Nordic Seas is not so easy to interpret. The high correlations may be coupled to high transport of warm water to the northern areas, which increase survivability of the larvae, while low correlations are associated with less northward transport of warm water and hence colder conditions and lower survivability.

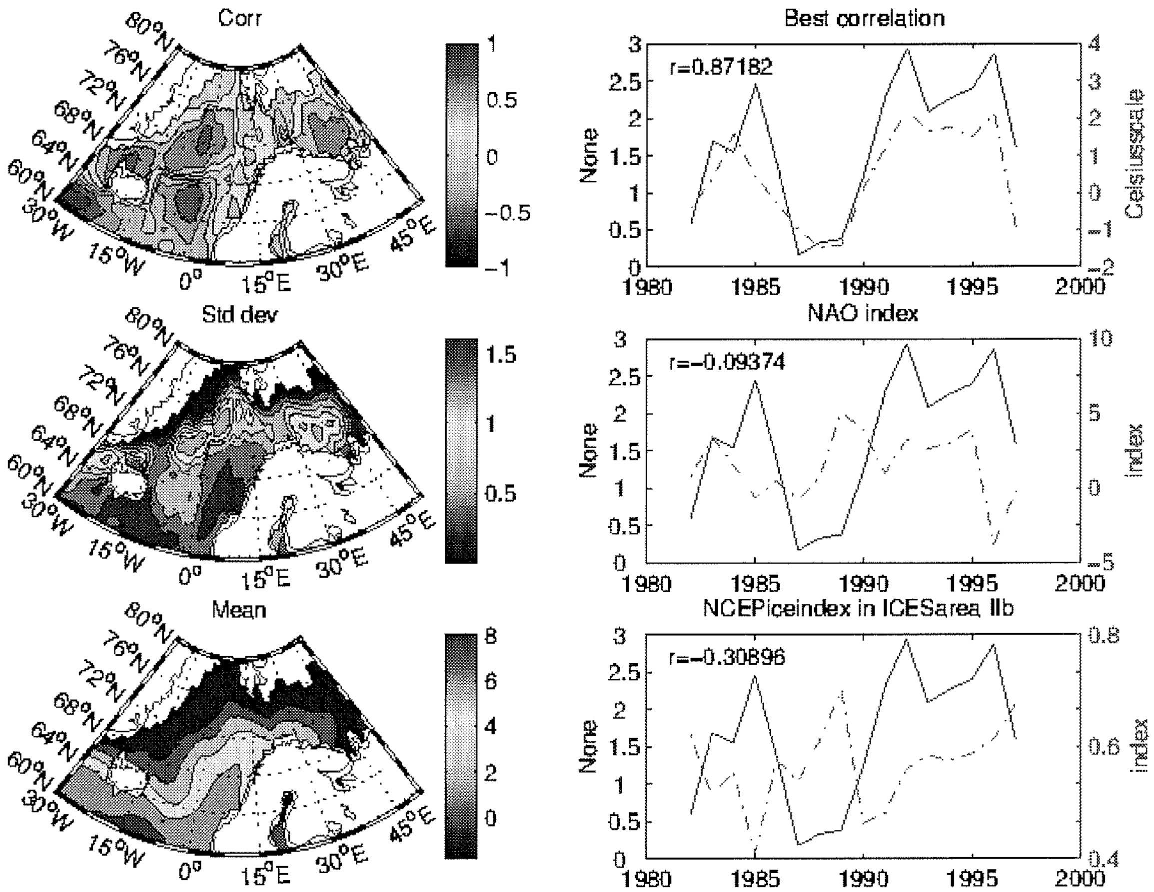


Figure 3. Correlation map between and supporting information 0-group index (log) of North East Arctic cod and IGOSS sea surface temperature (SST) in January the same year. Upper left panel shows the correlations, middle left panel the standard deviation of the climate variable, bottom left panel the mean of the climate variable, upper right panel the time series of the fishery time series and the climate variable in the grid cell with the highest correlation, middle right panel the fishery time series (0-group index) and the NAO winter index (Iceland –Lisbon) and the bottom right panel the time series of the fishery variable and the average NCEP ice index in January in ICES area IIb (around Svalbard, 0 is ice free). In all the three right panels the fishery time series are in blue solid line and left axis, while the climate variable is in green dashed line and right axis. Note that the timescale follows the biological variable. Note also that the best correlation (r=0.87) is in the Nordic Seas.

3. Sensible heat flux and Juvenile Index of North East Arctic cod

Figure 4 shows the correlation between NCEP sensible heat flux in January and North East Arctic cod juvenile index same year. The Juvenile index is based on a larvae cruise in June/July (only conducted during the years 1978-1991). The highest correlation (r=0.96) is found in one grid cell area east of Svalbard (the resolution is approx. 1.9x1.9 degrees). This is a region that mostly is covered by ice throughout the year (low sensible heat flux compared to water), but ice free/low ice concentration years appear occasionally. Though one should be careful to extract information from such a single point, even if the correlation is very strong, it is tempting to speculate about an explainable connection. The high correlation is driven by four very strong values, both in larval numbers and in the sensible heat flux (which means that there is low ice cover during these events), and is thereby strongly influenced by these extreme values. The ice cover movement passing such a point is mostly influenced by wind and the major circulation systems, with the current as a slow varying factor, thereby relatively more important on the inter-annual variation than the day to day variability. The larvae are hatched in April/May at Lofoten (North west coast of Norway), and can be found around Tromsø plateau (off Tromsø, Norway) at the time when the juvenile index is surveyed. It is therefore no direct connection between the two variables in question. We have to look for an explainable mechanism that lies behind both variables. The water temperature is a likely one. The warm water masses from south forces the ice cover northward and also influences the larvae growth and food supply positively, thereby increasing their survivability. The sensible heat flux in January at this point can therefore act as an indicator of larval survival, through the common driving force – the sea surface temperature.

In Figure 4, the bottom right figure shows the juvenile index together with the NCEP ice index in ICES fishery area IIb (see Fig. 1). The correlation coefficient between these two time series is –0.73, indicating a higher larval survival when there is low ice concentration (and thereby warmer water). This supports the above arguments.

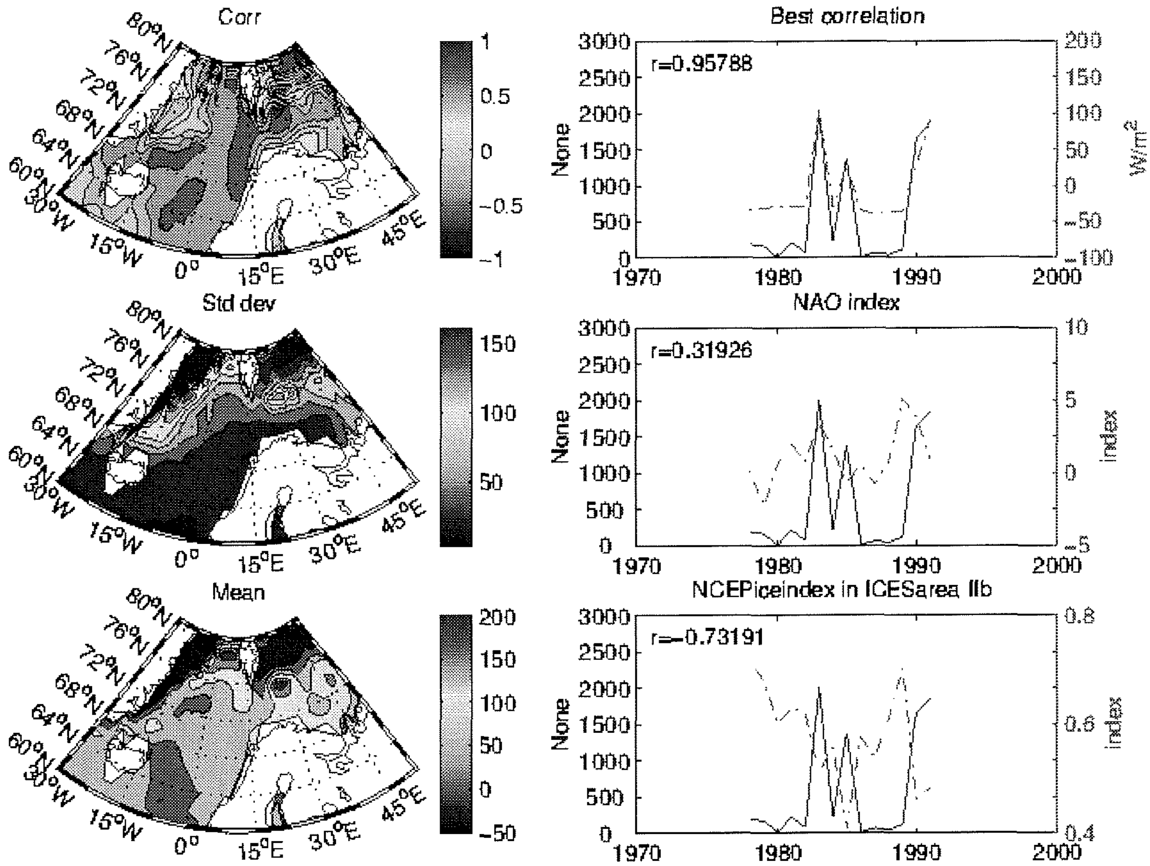


Figure 4. Correlation map between NCEP sensible heat flux in January and North East Arctic cod juvenile index the same year. See Fig. 3 for details.

3. Ice index and North East Arctic cod

A high negative correlation (r=-0.82) is found between the ice index from the MonArc dataset, which is calculated by use of the NORSEX algorithm (Svenden et al. 1983) and the recruitment (number of three year olds) from the ICES VPA 2002 assessment of North East Arctic cod two years later (Fig. 5).

The sea ice index may be seen as a measure of the northward transport of warmer water into the region, which will reduce the ice cover (lower ice indices). Warm water means better growth conditions when the cod was younger and better conditions for the zooplankton at that time. Low ice concentrations in January usually give less ice concentration later in the season, and thus a larger area for distribution, which might reduce cannibalism. Lager open area also allows more production of phytoplankton and zooplankton, which may give less competition for food for the young cod. These factors are favorable for the young cod, thereby giving the potential of a stronger year class of three year olds later (i.e. the number of three year olds).

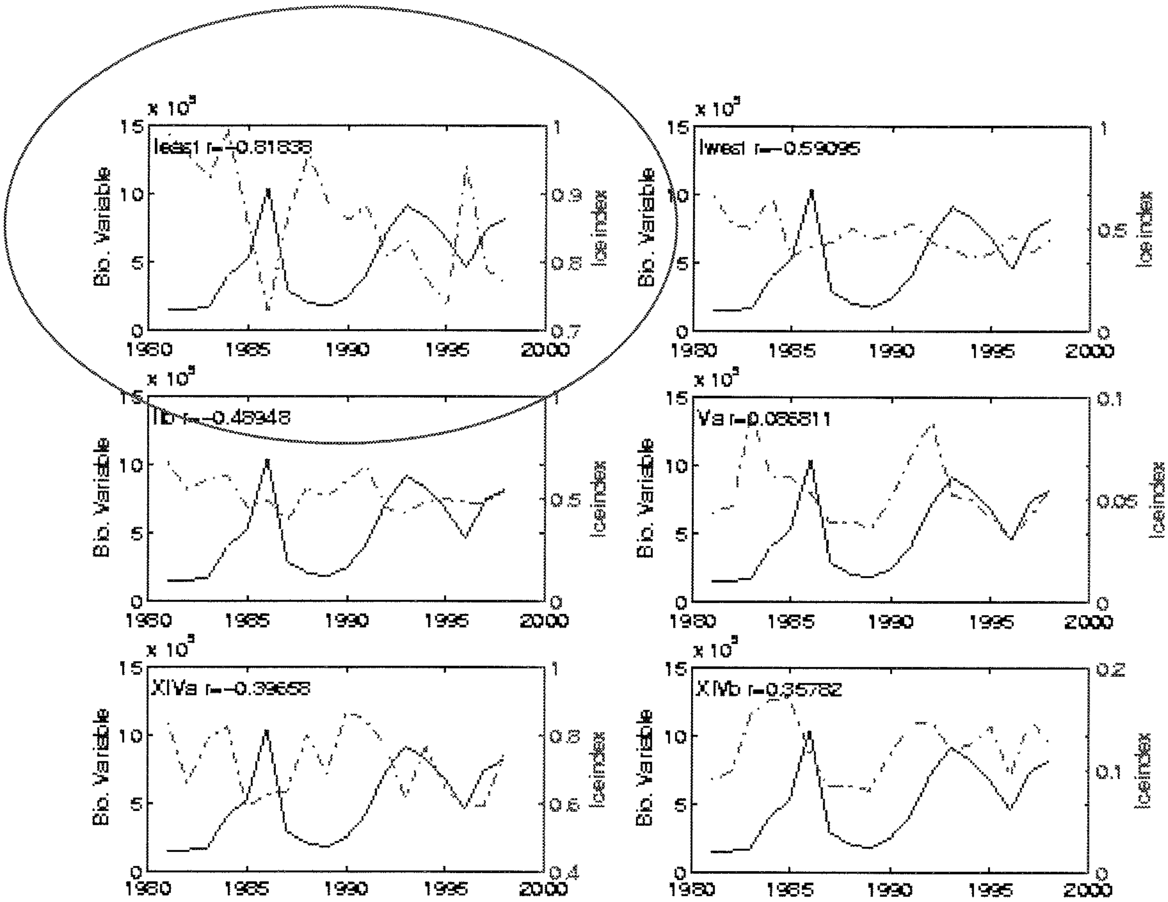


Figure 5. Time series and correlations between recruits (number of 3 year olds, VPA 1999, solid line) of North East Arctic cod and MonArc ice index (dashed line) in the ICES fishery areas (I east, I west, IIb, Va,XIVa and XIVb) in January 2 years earlier. Note the high correlation (r=-0.82) in area I east (Eastern Barents Sea, which is marked with a circle). Note that the timescale is for the biological (recruits) variable, with a two-year time lag for the physical data (ice index 2 year before recruits).

3.5 Multiple regression models

In some of the regression models used the fit may be equal or lower than for a plain correlation (e.g. Fig. 3 vs. Fig. 6 for 0-group index for cod and the NAO winter index). The reason for this is that focus in the multiple regression models has been to use as long time series as possible. In some cases adding more years gives a lower fit, but is still trustworthier due to lower uncertainty (because of more data points) to represent the natural variability.

3.5.1 0-group index of North East Arctic cod

A model for the 0-group log index of North East Arctic cod based on the NAO winter index (Lisboa-Iceland) and the spawning stock biomass (SSB) is tested.

The NAO index gives a good correlation (c=0.80) with the O-group index two years later, and a time lag of two year is therefore applied in the model. This time lag might be explained through food availability. Melle and Holst (2001) have found a high correlation between NAO and the zooplankton biomass in the Norwegian Sea the following year. This might imply that another year later food supply is still good for cod larvae on their drift northward along the Norwegian coast. The good recruitment of copepods may also use one year to be advected into the Barents Sea, giving a two-year time lag in the 0-group index.

For the SSB it is logical to use the spawning year that produces the larvae. SSB is calculates in VPA models from ICES for each January, while the 0-group index is calculated from survey data in the autumn.

A multiple regression model (Eq. IA, Fig 6A) for the 0-group index based on SSB the same year and NAO two years earlier explains 58 % (P-value < 0.01) of the variation in the 0-group index for the period 1966-2002 (Fig. 6A). The individual P-values were P_{NAO}=0.02 and P_{SSB}<0.01.

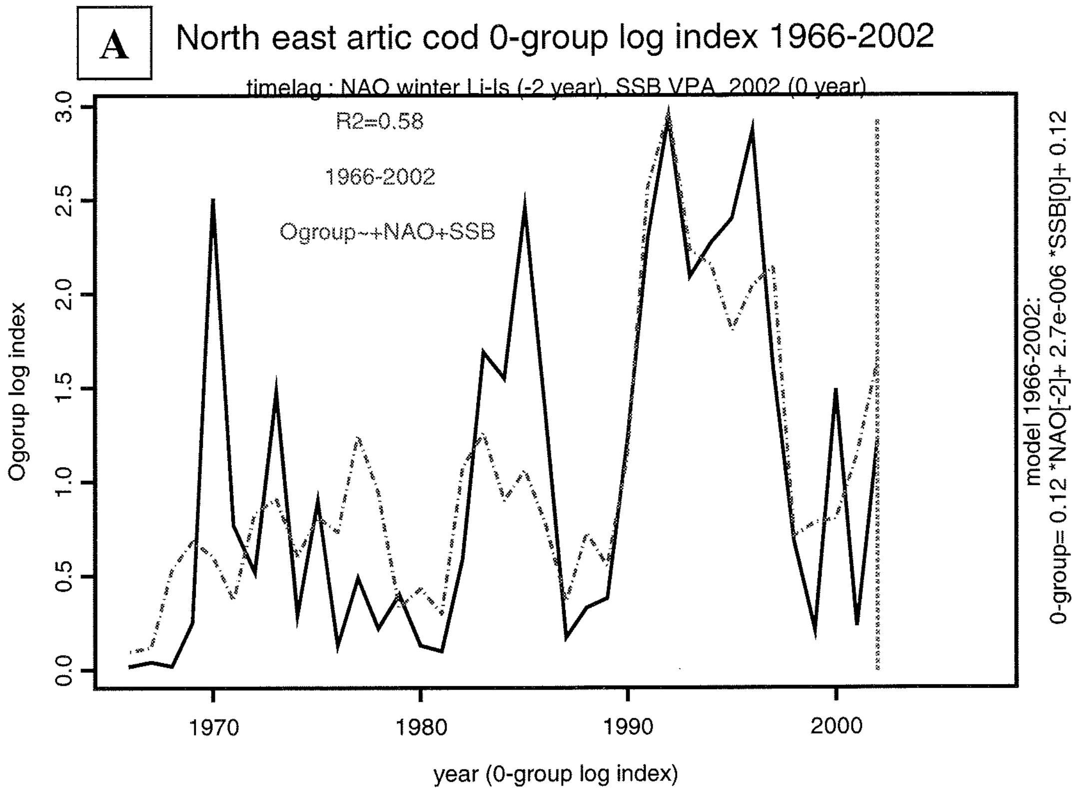
Model with coefficients:

$$0group_t = 0.12 \times NAO_{t-2} + 2.7 \times 10^{-6} \times SSB_t + 0.12 \qquad \text{(IA)}$$

$$0group_t = 0.19 \times NAO_{t-2} + 1.9 \times 10^{-6} \times SSB_{t-2} + 0.36 \qquad \text{(IB)}$$

where 0group is the log 0-group index, NAO the Lisboa-Island winter index and SSB the Spawning stock biomass (tonnes) from the ICES VPA 2002. The index denotes the time lag in years. Note that the difference between Eqs. IA and IB is that the SSB in the first has zero time lag while it has a time lag of two years in the latter.

In a model where one of the factors has zero time lag there is no potential for a prognoses. However, there is a high autocorrelation in the SSB from one year to the next. In the period 1946-2000 the autocorrelation was 0.90 and 0.71 for time lags of one and two years, respectively. By taking advantage of this autocorrelation it is possible to use the SSB two years earlier (the same lag as the NAO), and still have a reasonable good model. This trick makes it possible to generate a two-year prognosis for the 0-group index. This model is presented in Fig. 6B and Eq. IB. The model explains 49% of the variation, with individual P-values and total P-value of less than 0.01.



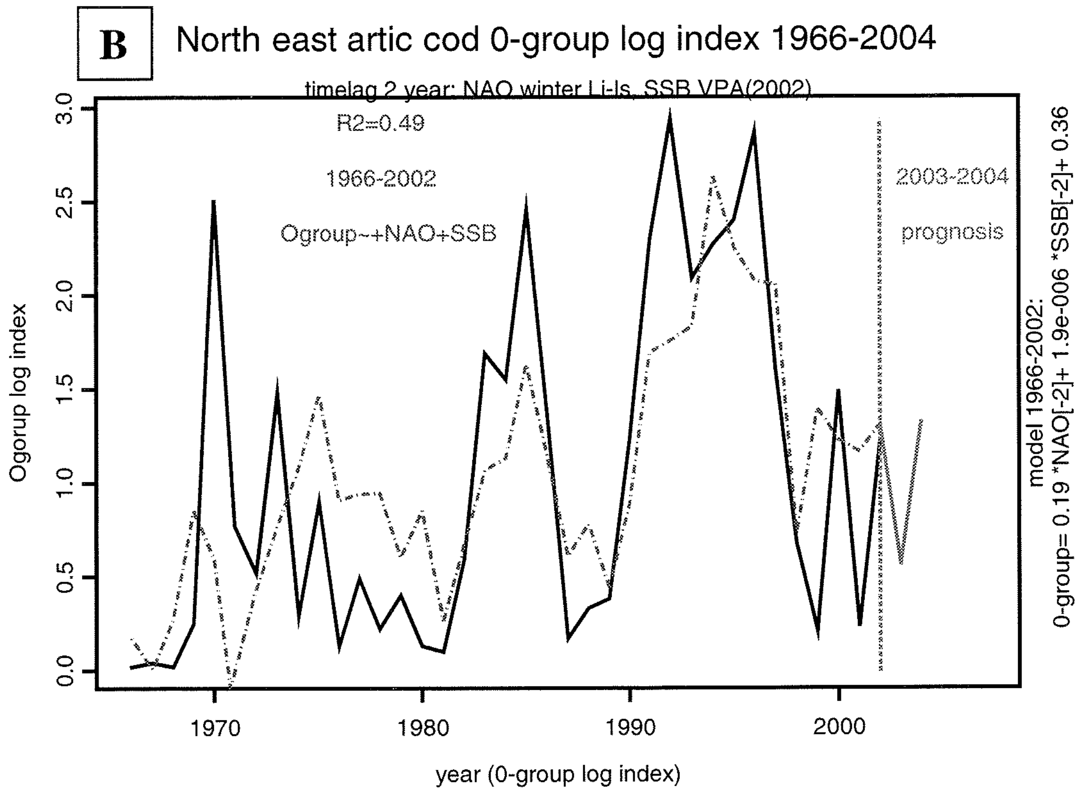


Figure 6. Multiple regression models for 0-group log index. North East Arctic cod. The model used is 0group index ~ NAO + SSB(VPA 2002). Figure A shows a model with two years time lag in NAO and no time lag in SSB, while Figure B shows a model with two year time lag in both NAO and SSB. The latter gives opportunity for a 2-year prognosis. Solid line is data, dashed is model and grey is prognosis. *Note that the timescale is for the 0-group index.*

3.5.2 Three-year-old recruits of North East Arctic cod (model 1)

A model of the spawning success (i.e. the number of three year old recruits per unit SSB) based on the NAO index and the spawning stock biomass (SSB) 3 year earlier explains 46 % of the variation for the period 1975-2002.

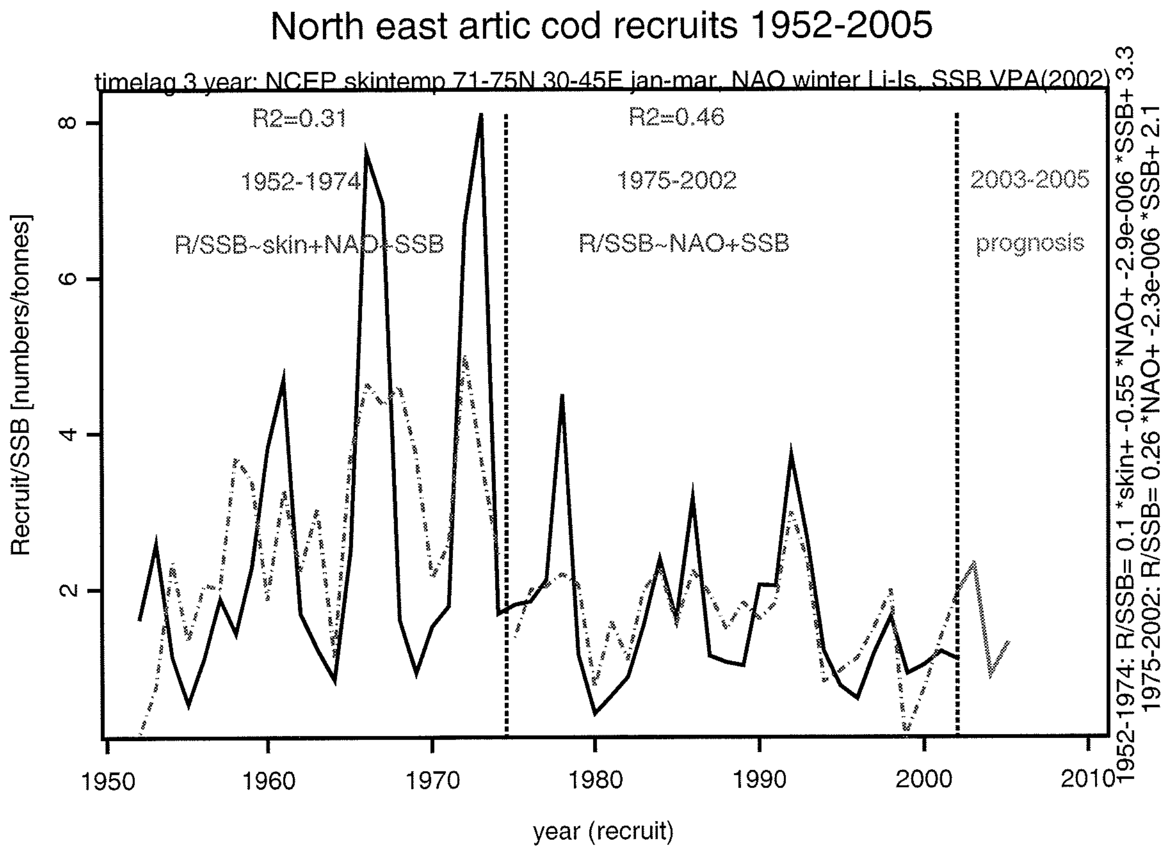


Figure 7. Multiple regression models for spawning success for North East Arctic cod, with prognoses for 2002-2005(solid grey line). The first model(dashed line) yields 1952-1974 and the second 1975-2002 (dashed line). The prognosis is calculated from the second model. Note that the timescale is for the biological variable. The time scale is for the recruitment. The solid line is the number of 3 year olds from VPA 2002,. Note that the timescale is for the recruitment.

Model (1975-2002) with coefficients:

$$\mathrm{Re}c_t \big/ SSB_{t-3} = 0.26 \times NAO_{t-3} - 2.3 \times 10^{-6} \times SSB_{t-3} + 2.1 \qquad \text{(II)}$$

By multiplying both sides of the equation with SSB the number of recruits can be expressed as:

$$\mathrm{Re}c_t = \left(0.26 \times NAO_{t-3} - 2.3 \times 10^{-6} \times SSB_{t-3} + 2.1\right) SSB_{t-3} \qquad \text{(III)}$$

where Rec is the number of recruits (in thousands), NAO the Lisboa-Island winter index and SSB the Spawning stock biomass (tonnes) from the ICES VPA 2002. The index denotes the time lag in years. The P-value for the model was less than 0.01 as well as all individual P-values.

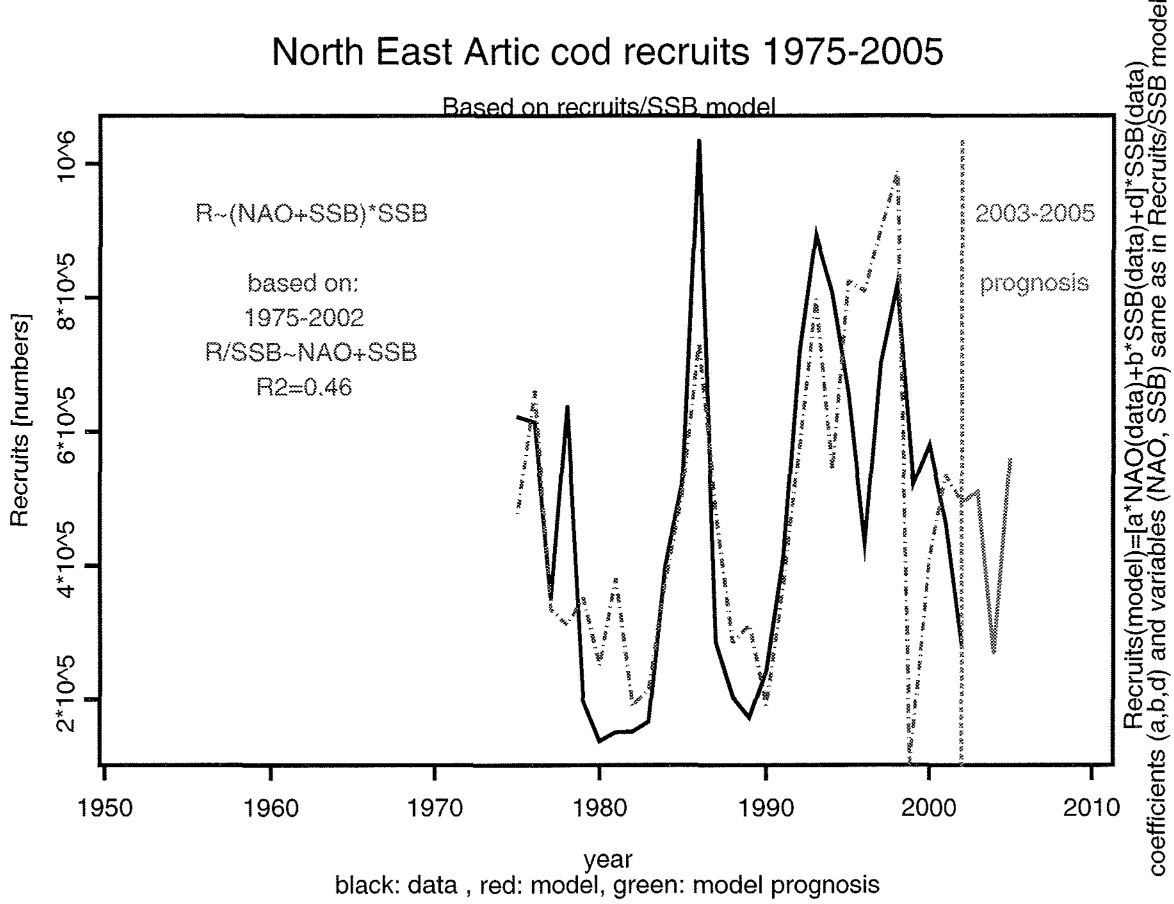


Figure 8. Recruitment (number of three year olds) of North East Arctic cod. The solid line is the VPA (2002) assessment data from ICES. The dashed line is based on the second model (Eqs.2 and 3) in Fig. 7, but multiplied by the SSB. Note that the timescale is for the recruitment variable. The grey solid line is the prognoses. Note that the time scale is for the recruitment.

For the time period before mid 70' this relationship fails. There seems to be two causes for this. First, there is a change in the position of the low-pressure field over Island after mid 70' (Hilmer and Jung, 2000), when it got a more eastward position, thus giving narrower isobars along the Norwegian coast for the same value of the NAO index as before mid 70' (i.e. stronger winds). Second, there is a shift in the distribution of the abundance in the age classes towards a higher abundance of younger spawners, while the number of older spawners decline. Therefore, another model have been used for recruitment before 1975. (This subject is further discussed in section 3.6)

Model (1952-1974) with coefficients:

$$\mathrm{Rec}_t / SSB_{t-3} = 0.1 \times skin_{t-3} - 0.55 \times NAO_{t-3} - 2.9 \times 10^{-6} \times SSB_{t-3} + 3.3 \qquad \text{(IV)}$$

where skin is the NCEP sea surface temperature (degree C) winter average (January –March) in the Barents Sea (71-75 N, 30-45 E). The other variables are the same as for the period 1975-2000. The index denotes the time lag in years. For this model R^2 is 0.31.

3.5.3 Three-year-old recruits of North East Arctic cod (model 2)

Another model for the number of three-year-old recruits of North East Arctic cod, developed by Geir Ottersen, IMR (pers. com.), have been tested on the data from the FJOMP database. The model uses an autoregressive term for the recruitment, using the recruitment one year earlier in the regression, and gives R^2= 0.57 for the years 1969-2002. The reason for using an autoregressive term is to allow for cannibalism and/or competition for food.

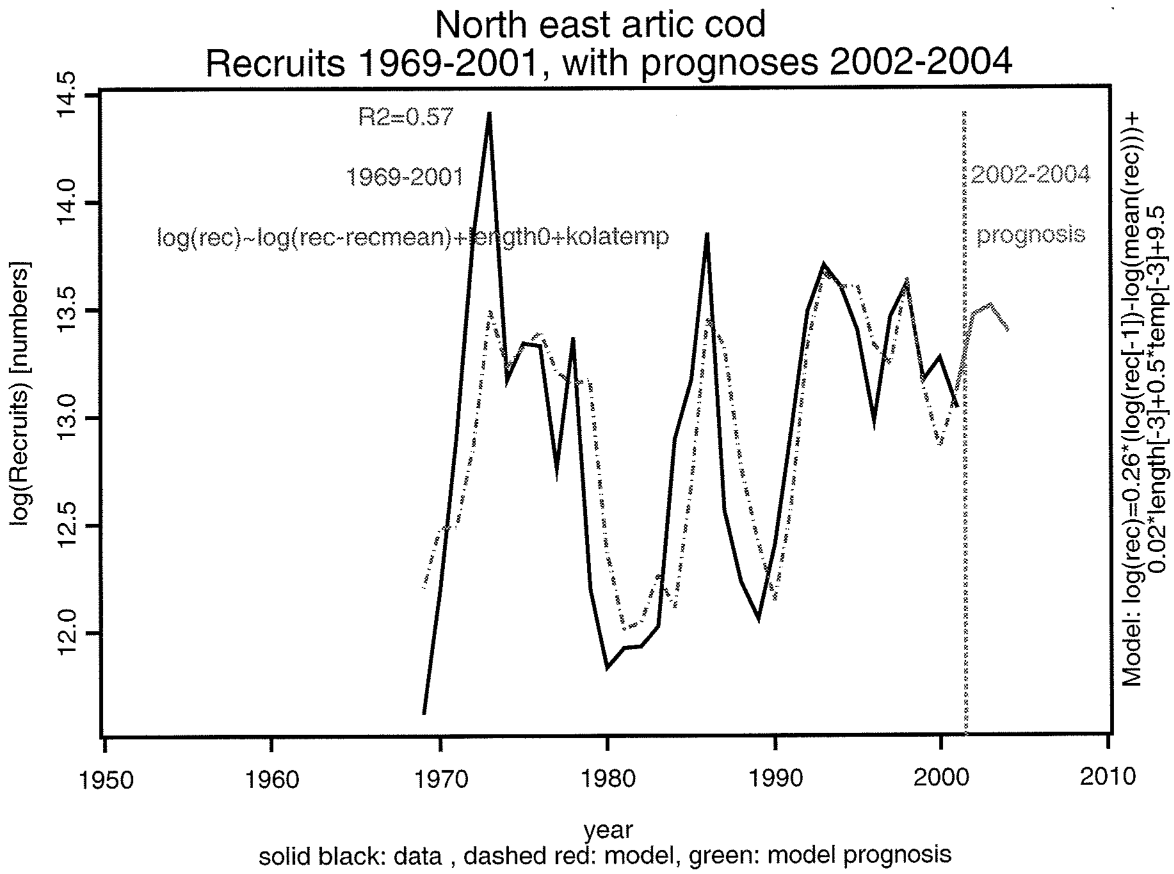


Figure 9. Recruitment (number of three year olds) of North East Arctic cod based on the multiple regression model by Geir Ottersen (from IMR), with prognoses 2001-2003. Solid line is the recruitment data, dashed line is the model and the grey solid line is the prognosis. Note that the timescale is for the recruitment.

The model with coefficients:

$$\log(rec) = 0.26\times\left(\log(rec_{t-1}) - \log(rec_{mean})\right) + 0.02\times length0_{t-3} + 0.5\times tempKOLA_{t-3} + 9.5 \quad \text{(V)}$$

where rec is the number of recruits (VPA, number of 3 year olds) in thousands, rec_{mean} the average recruitment for the period, $length_0$ the length of the 0-group larvae 3 year earlier and $temp_{KOLA}$ the yearly average temperature (degrees C) from 0-200 m in the Kola section 3 year earlier. The index denotes the time lag in years. Note that the 0-group length and the Kola temperature yield the year that the recruits were larvae. The P-value for the model is less than 0.01, with individual P-values: rec_{-1}-rec_{mean}=0.16, $length_{0\text{-}group}$=0.17, $temp_{Kola}$=0.04.

The model gives opportunity for a 3-year prognosis (Fig. 9), by using the calculated recruitment (left term in the equation) for one year as the input (first term on the right in the equation) the following year. Care must be taken since errors in the first year prognoses then are enhanced in the following years.

3.5.4 Three-year-old recruits of North East Arctic cod (model 3)

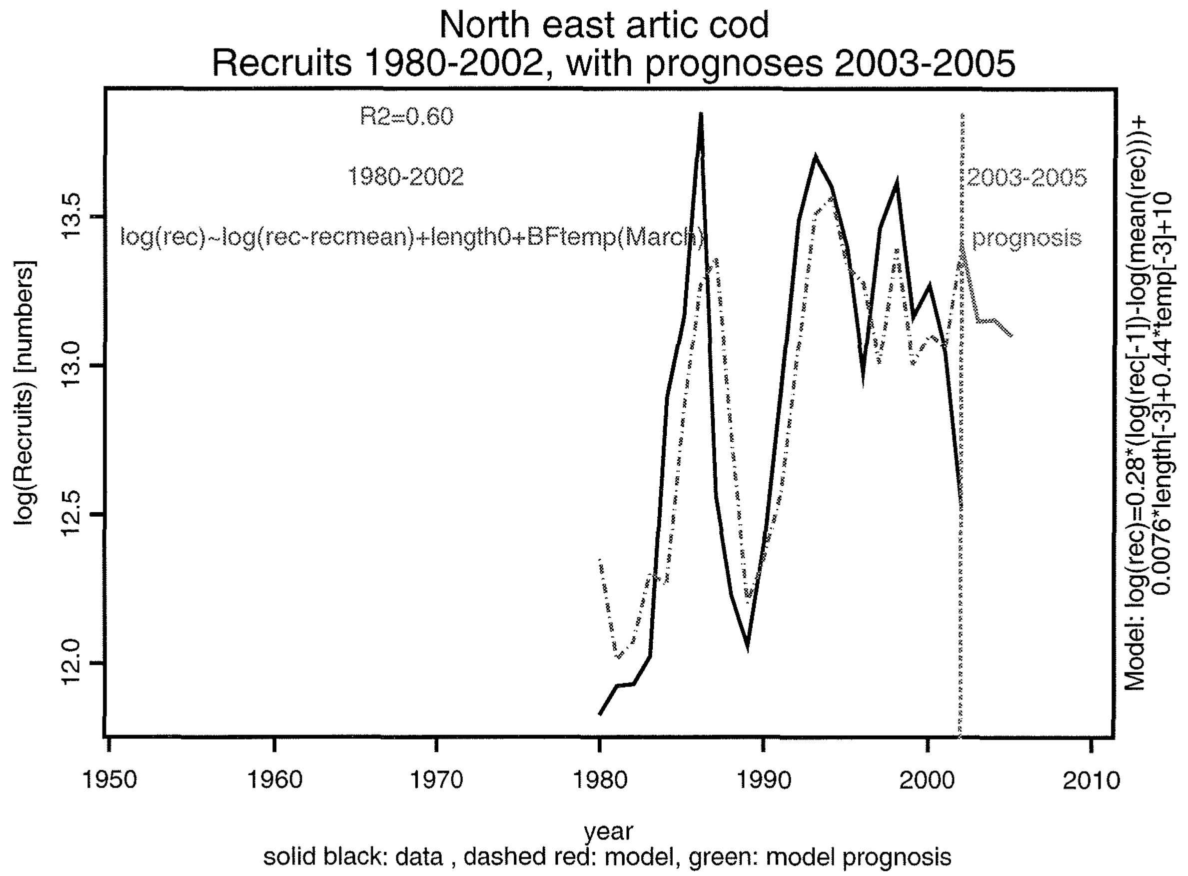


Figure 10. Same as Fig. 9 but with the temperature data from the Bjørnøya-Fugløya section instead of the Kola section. This allows the prognoses to be calculated to 2005. Solid line is the recruitment data, dashed line is the model and the grey solid line is the prognosis. Note that the timescale is for the recruitment.

The term that decides when the Ottersen model can be taken one year further is the yearly average Kola section temperature integrated over 0-200 m depth. This term is normally not available before January/February the following year. Therefore a variant of the model have been tested (Fig. 10), where the yearly average Kola section temperature has been exchanged with the average March temperature from 50 to 200 m in the Bjørnøya-Fugløya section (BF), which is available about 6 months earlier. The correlation coefficient between the two series is r=0.84 for the period 1980-2000. The Bjørnøya-Fugløya section was not routinely sampled before 1977, thus limiting the model to 1980 for recruitment. However, the model has a better fit to the data with R^2=0.60 and P-value < 0.01. However the individual P-values are not as good: rec_{-1}-rec_{mean}=0.62, $length_{0\text{-}group}$=0.36, $temp_{Kola}$=0.16).

The model with coefficients:

$$\log(rec) = 0.28\times(\log(rec_{t-1}) - \log(rec_{mean})) + 0.0076\times length0_{t-3} + 0.44\times tempBF_{t-3} + 10 \quad \text{(VI)}$$

where $temp_{BF}$ is the average temperature (degrees C) in March from 0-200 m in the Bear Island-Bird Island section 3 year earlier. The other variables are the same as in Eq V. The index denotes the time lag in years.

3.6 Change in cod spawning stock and climatic variability in the 70'

There seems to be a larger impact of climate variability on cod recruitment after the mid 70'. The NAO winter index gives a significant contribution to regression model (model 1, Eqs. II and III) after 1975, but for the period 1952-1974 this relationship is not evident. There might be both a biological and a physical explanation to this, which we will discuss.

First, the numbers of older spawners (older than 8 year) have declined rapidly during the last 50 years (Fig. 11). Simultaneously the age at which the cod gets mature have also declined, and there is presence of 3-year-old cod that spawn (which didn't occur earlier). With a younger aged spawning stock, the percentage of first time spawners, which have a lower egg quality, increase and these eggs and larvae are therefore more vulnerable to climatic variability.

Second, at the same time there seems to be a shift in the pressure field around Island (Fig. 12). The mean pressure field moves eastward, which means that with the same NAO index, the wind field is stronger along the Norwegian coast. Further, the NAO has larger oscillations with a period of about 8 years after the mid 70', which was not present in the previous period. This may be the reason that we find better couplings between the climate variables and recruitment of cod after the mid 70' than before (as indicated by the horizontal arrow in Fig. 11).

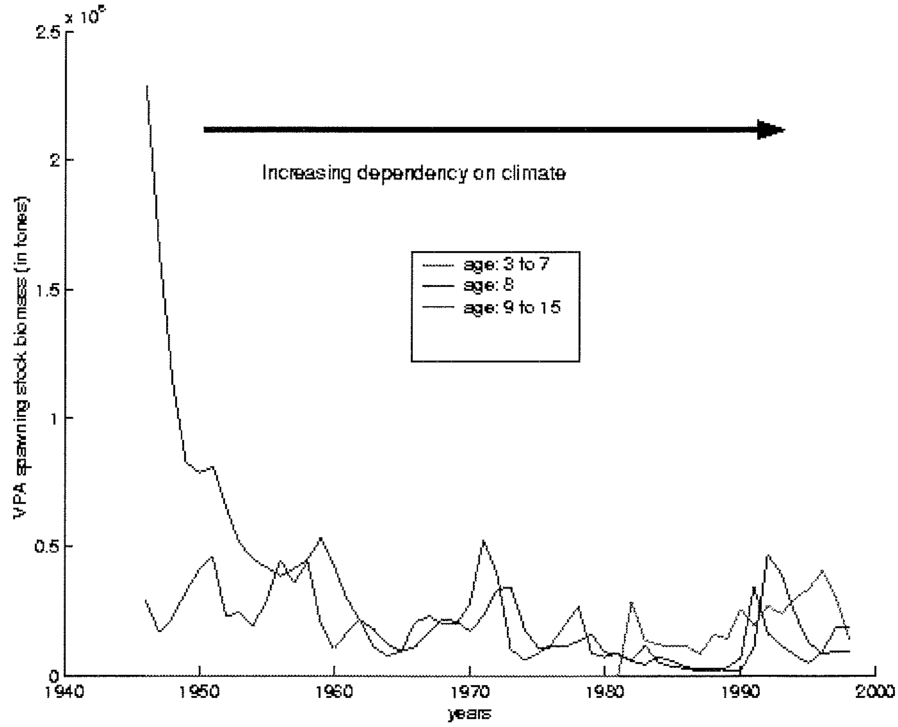


Figure 11. The development of the spawning stock biomass (VPA) of North East Arctic cod, divided into three age groups (3-7 year olds, 8 year olds and 9 + year olds).

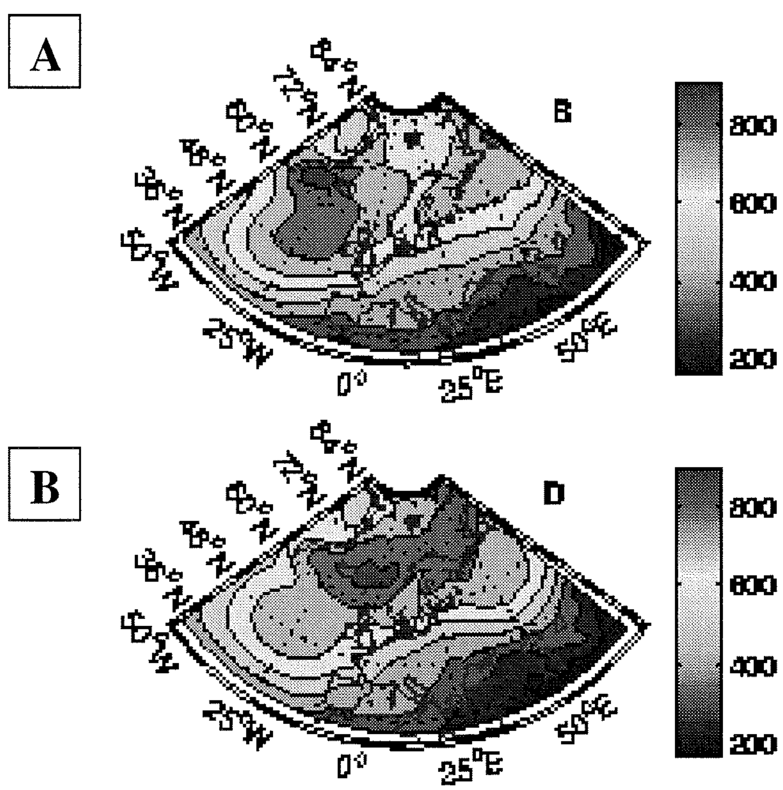


Figure 12. Shift in the winter low-pressure system location. A and B are the mean Sea surface pressure (SSP) in the periods 1948-1978 and 1975-1999, respectively. Please disregard the letters B and D within the figure. Note the shift to the east of the pressure field over Iceland for the second period.

3.7 Norwegian spring spawning herring

A model was tested for the number of three year old recruits of Norwegian spring spawning herring using the NAO winter index 5 years earlier, the herring 0-group log index 3 years earlier and the NCEP skin temperature 3 years earlier. The model described 85 % of the variation in the recruitment. Figure 13 show the model along with the recruitment data and a 3-year prognoses for the recruitment.

Model with coefficients:

$$\mathrm{Re}c_t = 39000 \times skin_{t-3} + 5400 \times NAO_{t-3} + 1.5 \times 10^5 \times 0group_{t-3} + 210000 \qquad \text{(VII)}$$

where Rec is the number (in 10^5) of 3 year old recruits of Norwegian spring spawning herring (VPA 2002 from ICES assessment), skin the NCEP skin (sea surface) temperature in degree C in the Norwegian Sea (64 -70 N, 6W – 8E) averaged from January to March, NAO the NAO winter index between Island and Lisboa and 0group the 0-group log index of herring larvae from survey in the autumn 3. The P-value for the model is less than 0.01, with individual P-values: P_{skin}=0.03, P_{NAO}=0.03, P_{0group}=0.01.

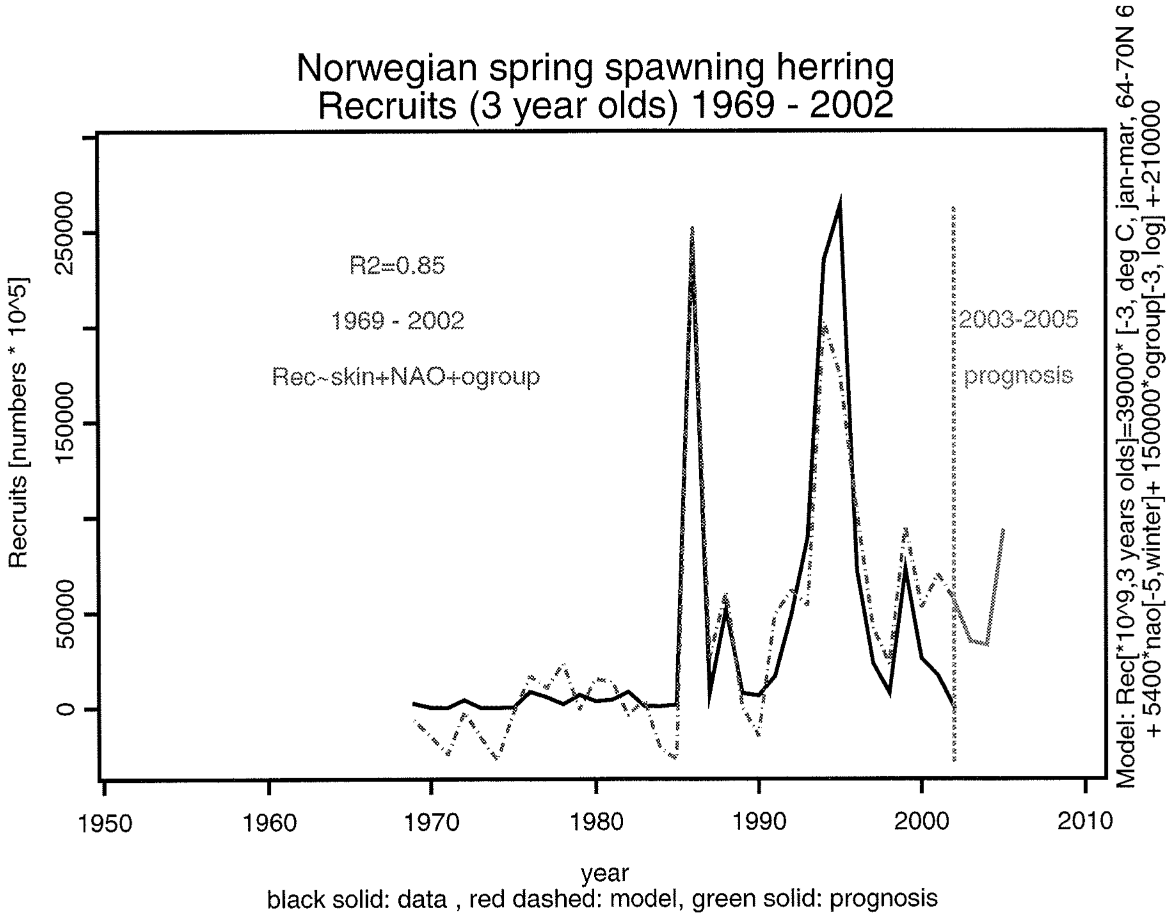


Figure 13. Multiple regression model for recruitment (3 year olds) of Norwegian spring spawning herring. Solid line is data, dashed line is model and grey solid line is a 3 year prognosis. Note that the timescale follows the recruitment, with NAO 5 years earlier and skin temperature and 0-group index 3 years earlier.

The dominant variable in the model is the 0-group index, which has an correlation coefficient of 0.89 with the Recruitment (3 years later). When the model was tested on the 0-group index alone it gave an R2 of 0.79. Still the model explained 6 % more of the variability when adding the climate variables. It is interesting to note that the NAO index gave the best result with a time lag of 5 years, which corresponds to 2 years before the larvae stage of the herring recruits. An explanation of this may be the food availability, following the same argumentation as for the 0-group of cod (section 3.1 and 3.5.1).

3.8 Barents Sea capelin

A model have been tested for the number of one year old recruits of Barents Sea capelin for the period 1982-2002 using NCEP skin temperature in the Barents Sea one year earlier, the capelin 0-group index one year earlier and the maturing biomass of capelin one year earlier. The model describes 72 % of the variation in the recruitment.

Model with coefficients:

$$\mathrm{Re}c_t = -37 \times skin_{t-1} + 0.45 \times 0group_{t-1} + 0.095 \times matbio_{t-1} - 57 \qquad \text{(VIII)}$$

where Rec is the numbers of one-year old recruits in 10^9, skin the NCEP skin (sea surface) temperature in Celsius averaged from January to March and over the area between 30-45 East and 71 to 75 North one year earlier (southern part of Barents Sea), 0group the capelin 0-group log index one year earlier (survey estimates back-calculated to 1 August) and matbio the capelin maturing biomass (length greater than 14 cm in 10^3 Tonnes) one year earlier.

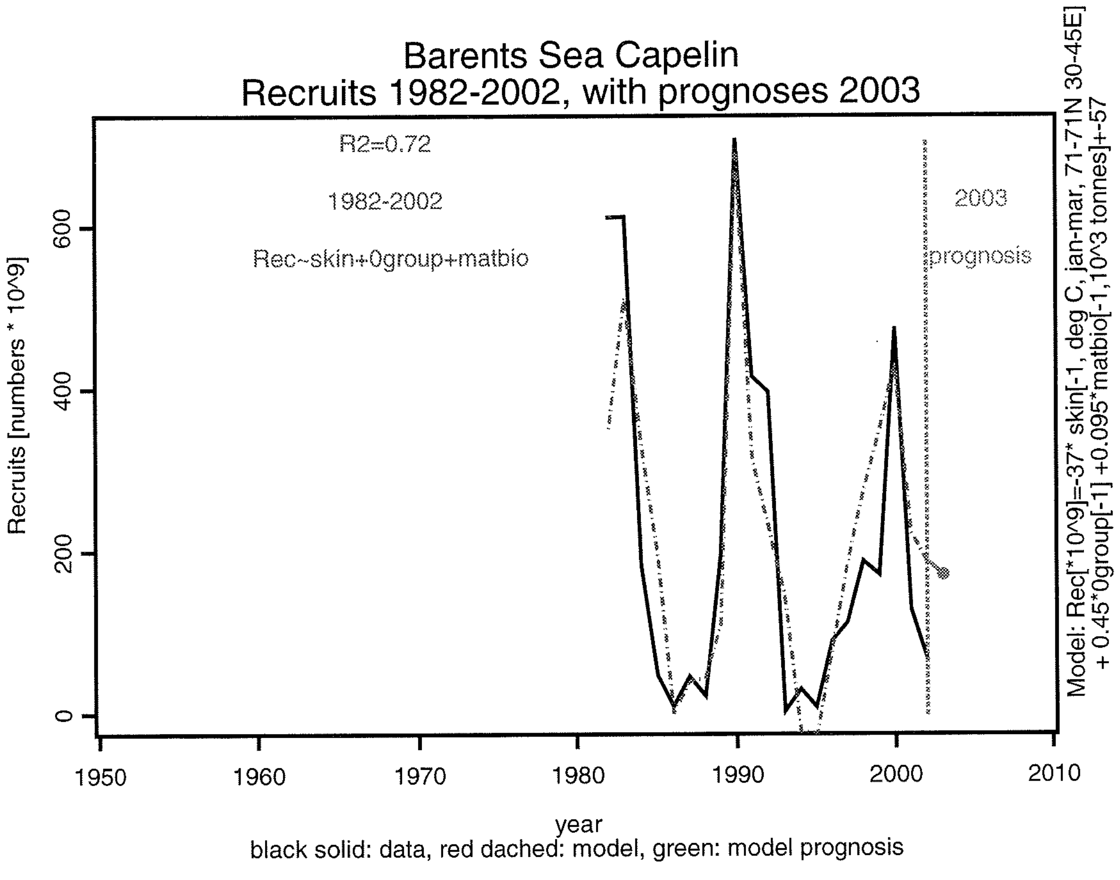


Figure 14. Number of one-year-old recruits of Barents Sea capelin (solid line) and the model fit (dashed line), together with prognoses for 2002 (grey solid line). Note that the timescale is for the recruitment and that the skin temperature, maturing biomass and 0-group index have a time lag of one year.

The P-value for the model is less than 0.01, with all individual P-values <0.04. The one-year time lag of the dependent variables gives opportunity of a prognosis one year ahead. Figure 14 shows the model together with the recruitment data and the one-year prognosis.

The dominant term in the multiple regression is the 0-group index, which have a high correlation (r=0.79) with the recruitment one year later. This gives an R^2 of 0.62 for a model with the 0-group index alone. By adding the climate variables the model improves 10 %.

3.9 Prognoses

Prognoses for recruitment to the fish stocks are of vital importance for fishery assessment and management. Also the commercial fishing fleet needs this information in decisions concerning future investment and fishing strategies. During the work with FJOMP we have managed to develop statistical and explainable models, with prognostic possibilities for a few of the key commercial species in Norwegian waters (Figs. 6-10, 14 and Eqs. I-III, V, VI, VIII).

The prognosis for the future recruitment estimated by the regression models (Eqs. I, III, V, VI, VIII) are given in Tab. 1. For North East Arctic cod several models are used. The difference in estimated values are due to two causes. First, the models are simplifications of the complex nature of recruitment and do not explain all the variation in the datasets and nature. Second, there is uncertainty in the input data used. Evaluations of these uncertainties have not been done. This should be a major point in future investigations.

In order to be of any practical use these statistical models need to be updated on an operational basis. The third column of Tab. 1 indicates which month the data is available for advancing the prognoses another year.

Summarized in Table 1 the following major predictive results have been obtained.

North East Arctic cod:

The regression model predicts a decrease in the 0-group index in 2003 followed by an increase in 2004, which will reach the same level as in 2002.

The three regression models (Eqs. III.V and VI, Figs. 8-10) for the number of 3-year-old recruits shows differences in both in the prognostic values and in the trend. However, neither of them indicates any extreme low or high recruitment for the prediction period. In general the three models show medium recruitment for the period 2003-2005.

Another indication on medium recruitment is given by the correlation between the 0-group log index and the number of three year old the next year. The correlation coefficient between these time series is 0.90 for the period 1978-1997. This means that a change in the 0-group index is followed by a likewise change in the number of three year olds the next year, and that the prognosis for the 0-group index (2003-2004) can be used as a trend prognosis for the number of recruits one year later (2004-2005). Though we don't believe there is any direct coupling between the 0-group index one year and the number of three year olds the next year the explanation may be found in couplings to the climate. As shown before there is a two year time lag between the NAO winter index and the O-group index and a three year time lag between the NAO winter index and the number of three year old.

Barents Sea capelin:

The regression model predicts a slight decrease in recruitment for 2003. However, the divergence between the model and the data imply that the prognoses might be overestimating the recruitment. The shape of the model curve the last years together with the oscillating pattern of the recruitment also points in the direction that the ongoing decrease in number of recruits since 2000 seems to have reached its low level, and that there might be a resonable chance of good recruitment the following years (after 2003/2004).

Norwegian spring spawning herring:
The regression model predicts a alight decrease in recruitment the next two years (2003 and 2004) followed by a moderate increase in recruitment in 2005. However, the divergence between the model and the data imply that the prognoses might be overestimating the recruitment.

Table 1. The table gives an overview of the different models, with prognoses estimates of the variable in question. The given month indicate when the prognoses can be extended for another year. N/A indicates that prognosis from he multiple regression model is not valid for this year. The t in the column "Prognosis available" indicates the year when the prognosis can be made, t is the first year in the prognosis. The model number1-3 refers to the models with the NAO index, Kola temperature and B-F temperature, respectively.

Species	**Variable (age)**	**Prognoses year**	**Prognoses available**	**2003 Prognoses**	**2004 Prognoses**	**2005 Prognoses**
North East Arctic cod	0-group, log (0 year)	2	October (t-1)	0.57	1.32	N/A
North East Arctic cod	Recruits (3 year) model 1	3	May (t-1)	$5.1*10^8$	$2.7*10^8$	$5.6*10^8$
North East Arctic cod	Recruits (3 year) model 2	3	January/ February (t)	$7.4*10^8$	$6.6*10^8$	NA
North East Arctic cod	Recruits (3 year) model 3	3	October (t-1)	$5.1*10^8$	$5.2*10^8$	$4.9*10^8$
Barents Sea capelin	Recruits (1 year)	1	October (t-1)	$1.7*10^{11}$	N/A	N/A
Norwegian spring spawning herring	Recruits (3 year)	3	October (t-1)	$3.5*10^9$	$3.3*10^9$	$9.2*10^9$

3.10 Sensitivity analyses
To test the multiple regression models for sensitivity of errors in the main climate variable a slight increase and decrease was added in the last year of the observation. The results are presented in Tab. 2.

For cod a change in the NAO index of +/- 0.5 did not influence the prognoses significantly (approx. 8%), while a change in the surface skin temperature by 0.5 degree C gave approx. 30% change in the number of recruits.

The number of capelin recruits changed approx. 25% for a change in surface skin of 0.5 degree C.

For herring a change in the NAO index of 0.5 changed the number of recruits only approx. 10%, while there were a change off approx. 20% in respect to surface skin temperature.

Table 2. Sensitivity analyses for response in the climate variable for the different regression models. The climate variable has been shifted +/- 0.5 in the last year of the prognoses. N/A indicates that the prognoses is not valid for these runs, and "-" indicates that this is not the last year of the prognosis and are therefore not calculated. For the herring model both the NAO index and skin temperature have been evaluated. The model number1-3 refers to the models with the NAO index, Kola temperature and B-F temperature, respectively.

Species	**Response variable (age)**	**Climate variable**	**Change in climate variable**	**2003 prognoses**	**2004 prognoses**	**2005 prognoses**
North East Arctic cod	0-group index	NAO	0.5	-	1.42	N/A
			0	0.57	1.32	N/A
			-0.5	-	1.23	N/A
North East Arctic cod	Recruits (3 year) model 1	NAO	0.5	-	-	$6.1*10^8$
			0	$5.1*10^8$	$2.7*10^8$	$5.6*10^8$
			-0.5	-	-	$5.0*10^8$
North East Arctic cod	Recruits (3 year) model 2	Temp.	0.5	-	$8.4*10^8$-	N/A
			0	$7.4*10^8$	$6.6*10^8$	N/A
			-0.5	-	$5.1*10^8$-	N/A
North East Arctic cod	Recruits (3 year) model 3	Temp.	0.5	-	-	$6.1*10^8$
			0	$5.1*10^8$	$5.2*10^8$	$4.9*10^8$
			-0.5	-	-	$3.9*10^8$
Barents Sea capelin	Recruits (1 year)	Temp.	0.5	$1.5*10^{11}$	N/A	N/A
			0	$1.7*10^{11}$	N/A	N/A
			-0.5	$1.9*10^{11}$	N/A	N/A
Norwegian spring spawning herring	Recruits (3 year)	Temp.	0.5	-	-	$11.2*10^9$
			0	$3.5*10^9$	$3.3*10^9$	$9.2*10^9$
			-0.5	-	-	$7.3*10^9$
		NAO	0.5	-	-	$9.5*10^9$
			0	$3.5*10^9$	$3.3*10^9$	$9.2*10^9$
			-0.5	-	-	$8.9*10^9$

4. Summary and conclusions

The effect of climate variation on fish recruitment and stock status has been investigated. Climate and fishery variables in the FJOMP database has been systematically correlated, also with various time lags (1-3 years), in order to search for interesting relationships. Multiple regression models have been used to further improve some of the most interesting correlations found. In the following the most interesting identified relationships between climate variables and fish recruitment are listed.

- A correlation of 0.82 for a time lag of two years between the North East Arctic cod 0-group index and the NAO winter index for the period 1978-1997.
- A correlation of 0.87 for zero time lag between the North East Arctic cod 0-group index and the IGOSS sea surface temperature in the Nordic Seas in January for the period 1982-1997. High correlations were also found in the southeastern parts of the Barents Sea.
- A correlation of 0.96 with zero time lag between the North East Arctic cod juvenile index and the NCEP sensible heat flux in a point east of Svalbard (at the ice edge) in January for the period 1978-1991.
- A correlation of – 0.81 for a time lag of two year between the number of recruits (three year olds) of North East Arctic cod and the MonArc ice index in the eastern part of the Barents Sea (ICES area I east) in January for the period 1981-1998.
- A regression model describing 49 % of the variance for the 0-group index of North East Arctic cod based on the NAO winter index and the spawning stock biomass two year earlier for the period 1966-2002.
- A regression model describing 46 % of the variance for the number of recruits (three year olds, VPA) of North East Arctic cod based on the NAO winter index and the spawning stock biomass three year earlier for the period 1975-2002.
- A regression model describing 57 % of the variance for the number of recruits (three year olds, VPA) of North East Arctic cod based on the recruitment (three year olds) the year before, the length of the 0-group larvae and the yearly average temperature in the Kola section three year earlier for the period 1966-2001.
- A regression model describing 60 % of the variance for the number of recruits (three year olds, VPA) of North East Arctic cod based on the recruitment (three year olds) the year before, the length of the 0-group larvae and the average temperature in March in the Bear Island-Bird Island section three year earlier for the period 1980-2002.
- A regression model describing 85 % of the variance for the number of recruits (three year olds) of Norwegian spring spawning herring based on the average NCEP skin temperature in the Norwegian Sea and the 0-group index three year earlier and the NAO winter index five years earlier for the period 1973-2002.
- A regression model describing 72 % of the variance for the number of recruits (one year olds) of Barents Sea capelin based on the average NCEP skin temperature in the Barents Sea , the 0-group index and the mature biomass one year earlier for the period 1982-2002.

The NAO index and sea surface temperature are the two climate factors that seems to be the most important for the fish recruitment, although sensible heat flux, sea ice cover and heat transport (into the Barents Sea) also are found to give good relations towards fish recruitments. Especially the NAO index gives good relations to several recruitment parameters for North East Arctic cod, while the sea surface temperature is more important for Barents Sea capelin and Norwegian spring spawning herring.

In this study we have acquired a large database (FJOMP) of more than 70 marine environmental and fishery stock related datasets. Without any prejudices and using up to three years of time lag between the time series we have searched through these data to identify correlations that are significant. In this process more than 200 sets of correlations with a correlation coefficient better than +/- 0.7 were identified. Through an individual inspection of these relations most of them were discarded (due to unrealism or not "explainable" at present) and a remaining 20 cases were evaluated as highly interesting, with an explainable cause for the identified variations.

The analysis presented is just a start on "scratching" on the information included in this coupled physical and fishery marine database. To fully exploit the values of this database it needs to be maintained with new data records and the methods of analysis and evaluation should be refined in order to become more robust.

Since this work indicates clear effects on recruitment from climate, it is a great challenge to investigate these effects together with multi-species population dynamics, especially including cod, herring and capelin simultaneously.

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